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How can we keep structural integrity of the first wall having micro cracks?

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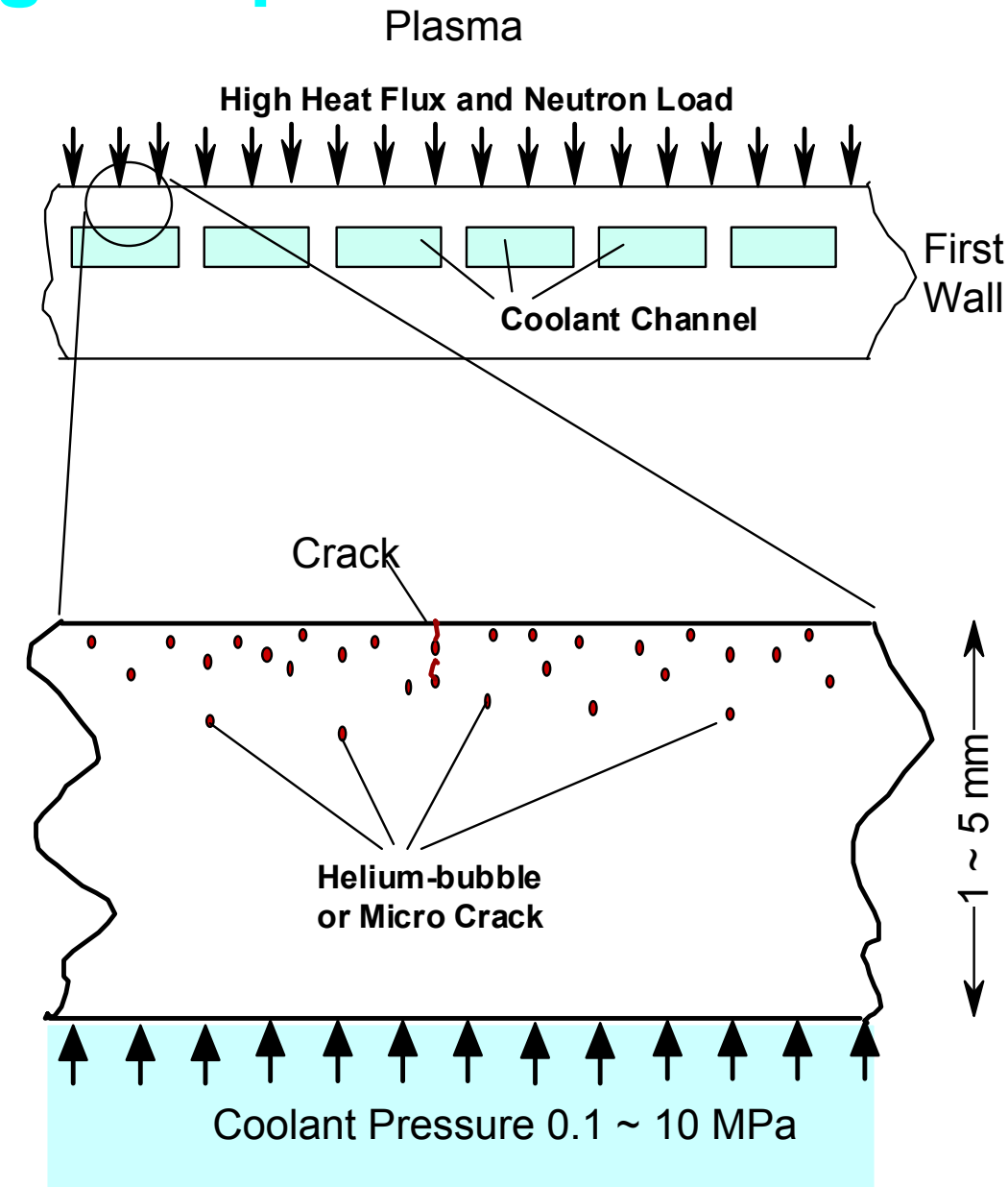
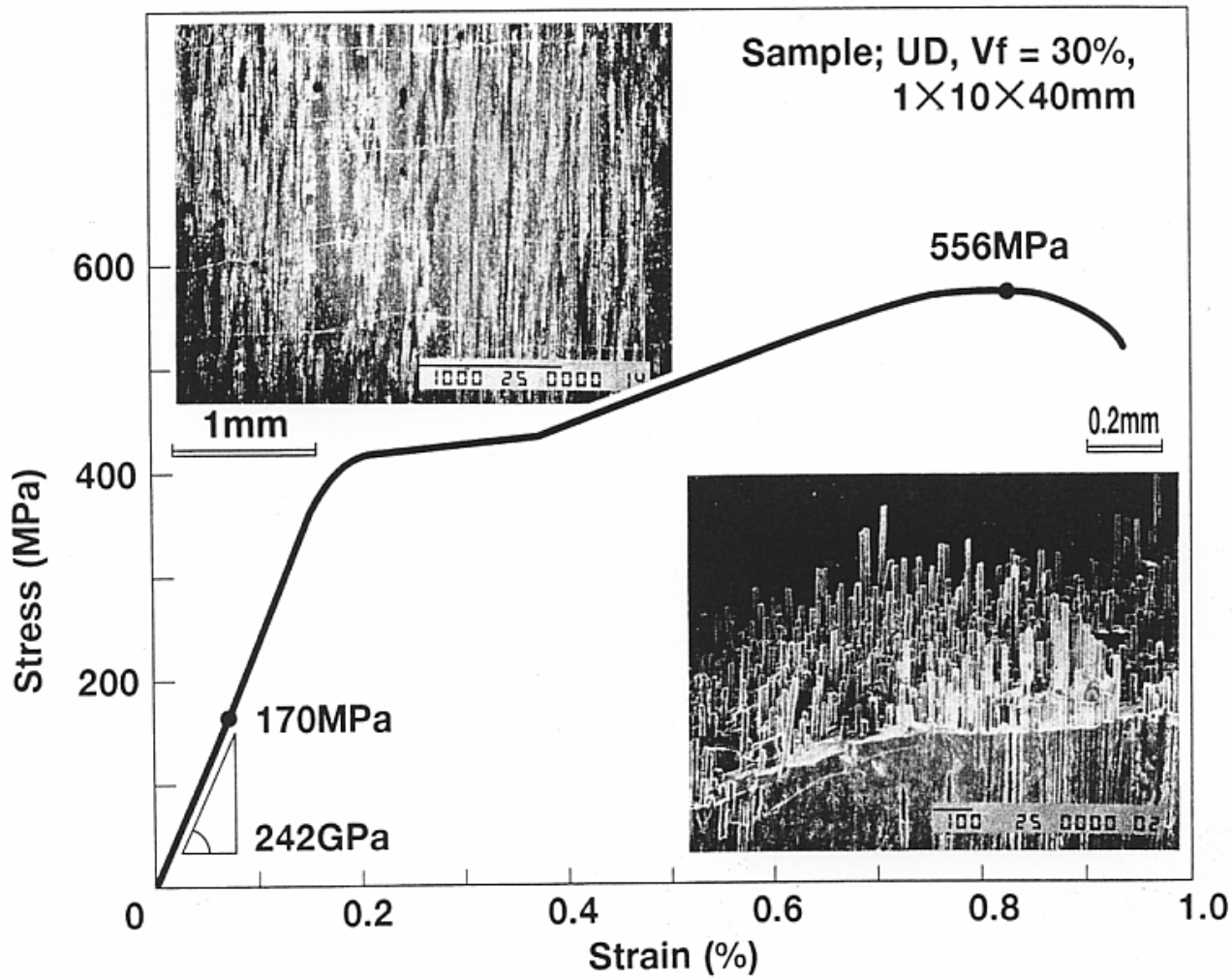
Plasma Facing Components

- **The first wall made of any material such as ferrite steel, tungsten and SiC/SiC composite material must have micro cracks or Helium-bubbles due to transmutation reaction with neutrons.**
- **Thermal stress and coolant pressure load in the first wall might initiate to propagate those micro cracks.**
- **If those micro cracks were combined into a significant crack during life of the components, the first wall is difficult to endure a high pressure load by the coolant.**



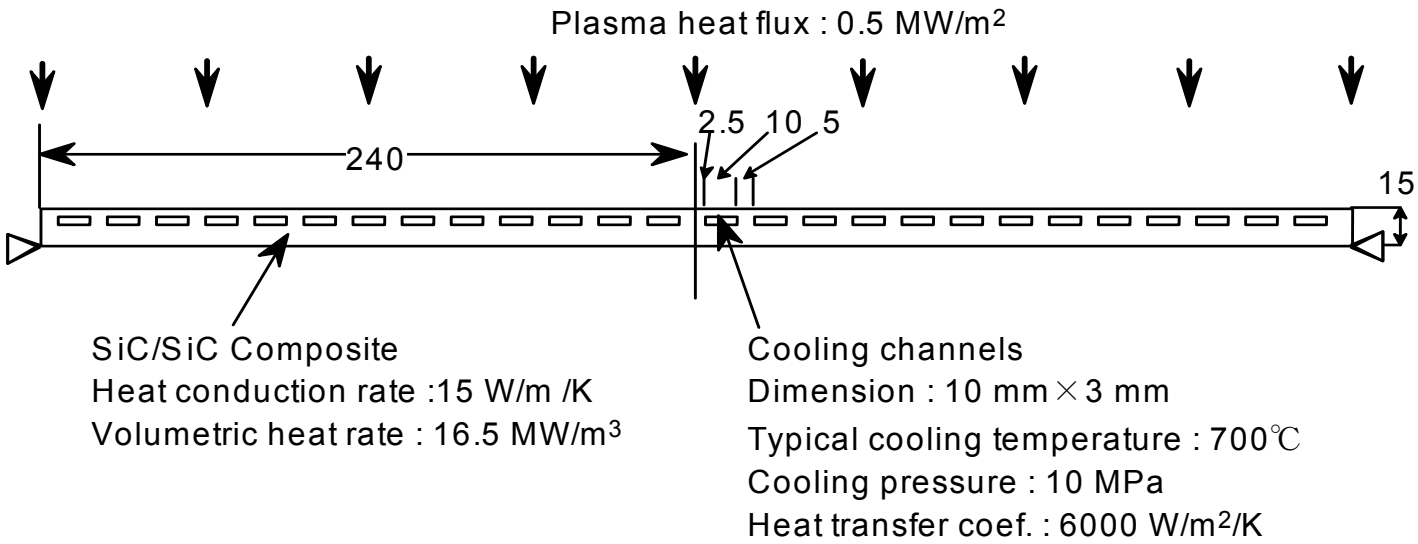
Micro Cracks in SiC/SiC Material

- SiC/SiC composite material would have many micro cracks along SiC fibers when it is under plastic state.
- How could we avoid the combination of micro cracks in SiC/SiC composite?
- This mechanical issue is difficult to be solved by the material study only.
- I evaluated fracture mechanics of a crack generated at surface of the first wall using FEM



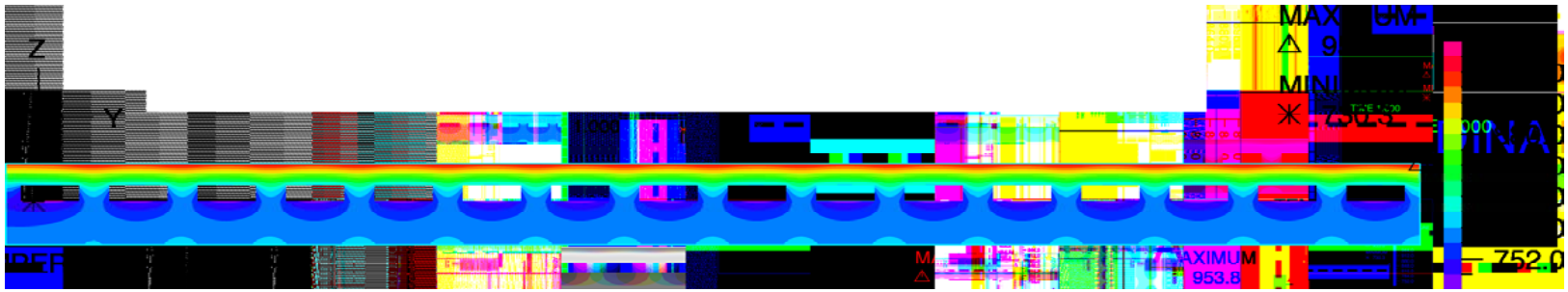
Y. Itoh, et al., J. Ceramic Society of Japan, v.106, 1190-1195 (1998)

First Wall Analysis Model



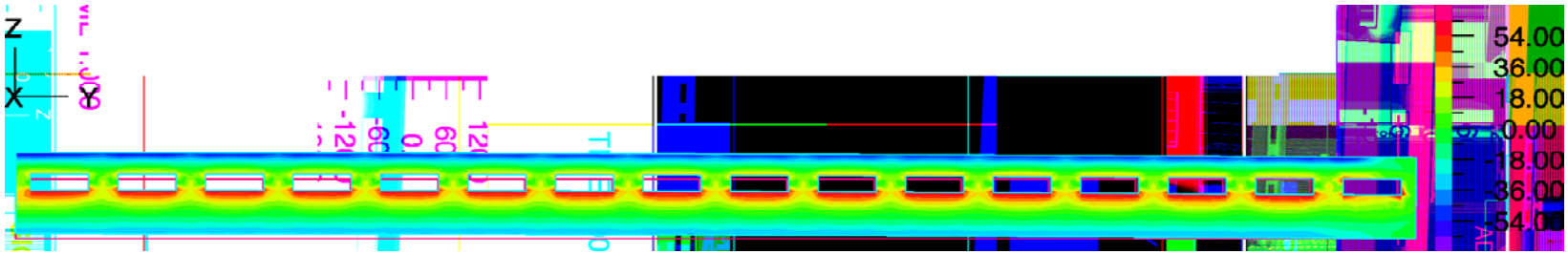
- **Bending stress due to thermal expansion generated from one side heating can not be ignored when the first wall is not perfect hemisphere-shaped.**
- **DREAM blanket first wall is assumed 480 ϕ circular plate having no curvature in order to evaluate bending stress conservatively.**
- **0.5 MW/m^2 heat flux from the plasma was caught at one side on the first wall of the thickness 4 mm cooled by the He gas of pressure 10 MPa and temperature 700 ℃.**

Temperature profiles of the first wall



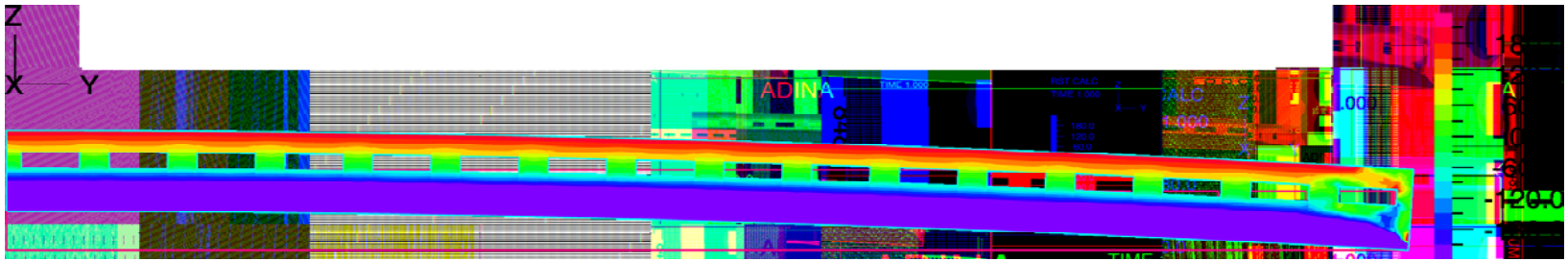
- **The maximum temperature is calculated 954℃. This value is below the operating temperature limit of SiC/SiC composite, 1100℃.**

Displacement and Bending Stress in Case of Free Edge



- **When thermal expansion of the first wall is not constrained, distribution of displacement and bending stress due to the internal pressure of 10 MPa and the temperature difference is shown in this figure.**
- **The maximum displacement is 0.9 mm at the center. The maximum bending stress is 60 MPa at the plasma side surface.**

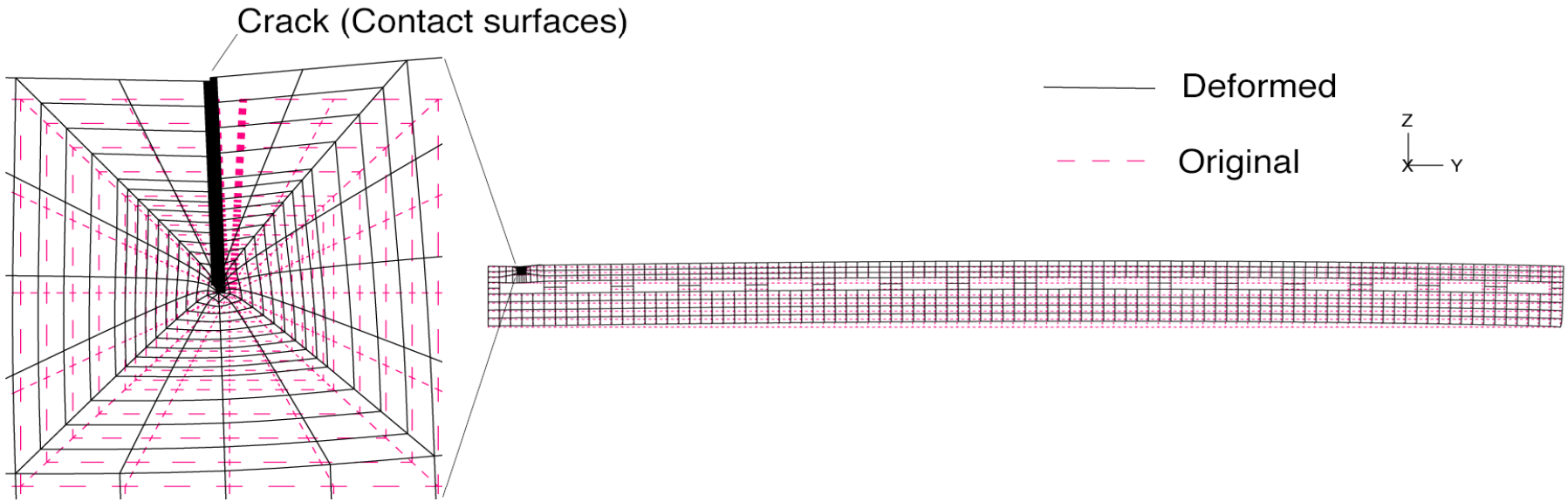
Displacement and Bending Stress in Case of Restrained Edge



- When the thermal expansion of the first wall is restrained at the edge, the maximum displacement is 7.3 mm at the center.
- The maximum bending stress is 280 MPa at the plasma side surface in elastic analysis, which is over the allowable stress of SiC/SiC composite, 200 MPa.
- It is necessary to find a new device for releasing thermal expansion in the design of the first wall.

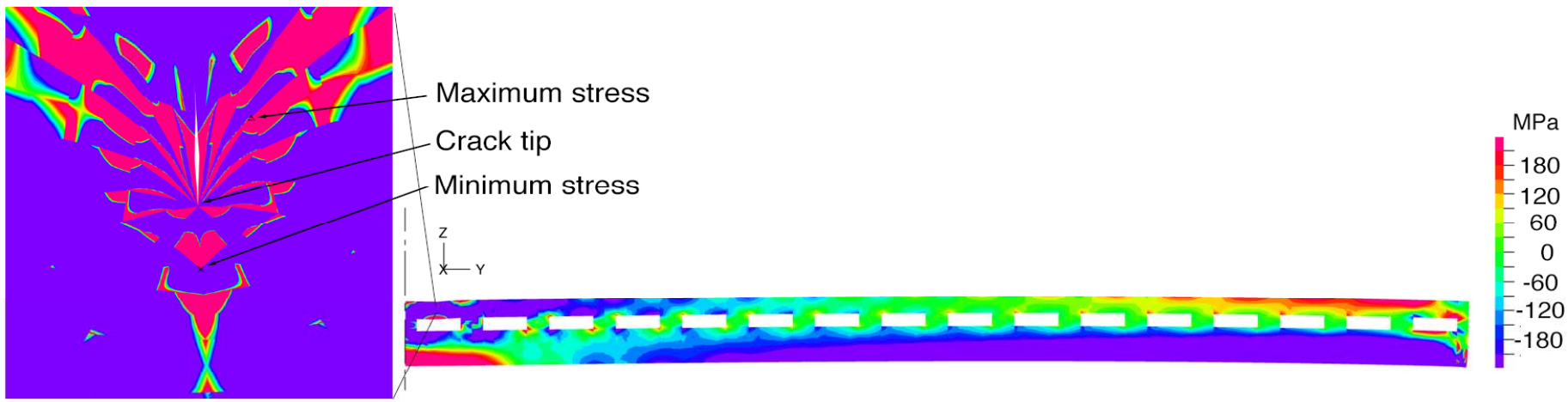
Displacement of the First Wall with a Crack

- **Figure shows the calculated displacement of the first wall with a crack of depth 1.0 mm on the plasma side under thermal expansion bending load.**
- **Initial condition and boundary condition of this model are the same with those of the last figure, except having a crack.**
- **This was calculated using nonlinear thermal-plastic material model with stiffness reformation and equilibrium iterations of 50 load steps by ADINA finite element analysis code.**
- **Nodes on the two crack faces use the contact surface condition each other.**
- **Thermal expansion around the crack is released and maximum displacement is 1.5 mm.**



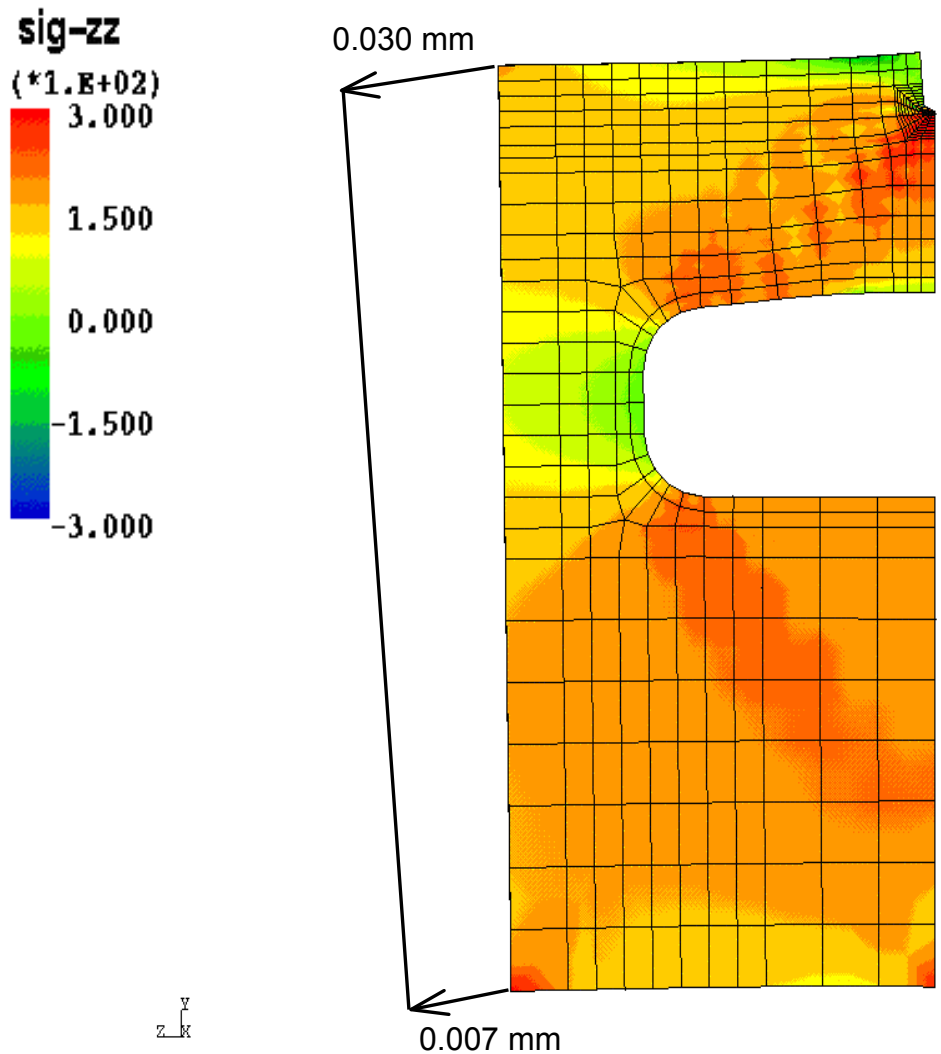
Bending Stress of the First Wall with a Crack

- **Figure shows calculated bending stress distribution of the first wall model with a crack.**
- **Bending stress around the crack is almost compressing state.**
- **Tensile stress concentration are resulted in very tiny region around the crack tip.**
- **Pressure of 10 MPa is loaded in the cooling channel, so the primary stress would affect the crack tip if the crack deepens.**
- **Crack might propagate if the fracture mechanics parameter such as J-integral value exceeds the fracture toughness value.**
- **It is necessary to consider the creep relaxation for accurate evaluation of the stress distribution around the crack tip.**



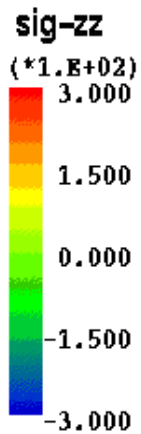
Cracked First Wall Subjected to Displacement Controlled Load

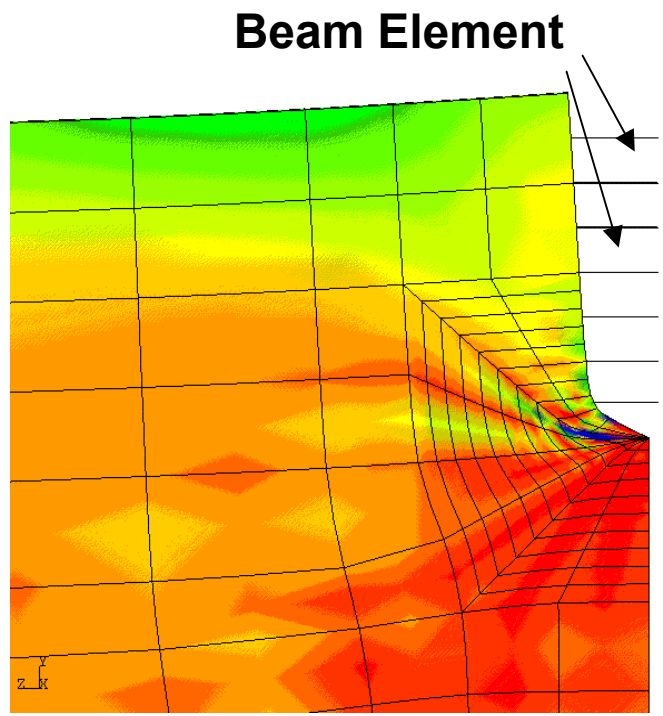
- Figure shows calculated displacement and stress distribution of cracked first wall subjected to displacement controlled load.
- Crack depth is 1.0 mm in the plasma side front face of first wall.
- Elastic-plastic finite element analysis showed a crack opening displacement of 54.8 micron and J-integral value of 9.6 kN/m.
- Stress intensity factor K_I value corresponding to J-integral value of 9.6 kN/m is over the fracture toughness K_{IC} , 3.3 MPa $m^{1/2}$, so crack is not stable.



First Wall With a Crack Having Fiber Bridging

- Figure shows calculated displacement and bending stress of the first wall with a crack having fiber bridging.
- A fiber was modeled by a beam element having diameter of 50 micron.
- Crack opening displacement was 30.2 micron. J-integral value around crack tip was 1.9 kN/m.
- Crack might be arrested, because K_I value is less than the fracture toughness K_{IC}.





Discussion

- High toughness and damage tolerance which is the excellent mechanical characteristics of the SiC/SiC composite are realized by allowing the formation of many micro cracks in the matrix due to SiC fiber pulling out.
- Coalescence and growth of the multiple micro cracks must be important integrity issue to use the SiC/SiC composite as the blanket material.
- Even if the crack growth was arrested, however, there is another problem that the tritium or helium in a coolant might penetrate through the micro cracks.
- In that case, function of the leak tight is not kept, even if the integrity of the first wall was ensured.
- In the actual operation, thermal fatigue due to plasma startup and shutdown, creep due to high heat flux, irradiation creep and interference of the multiple cracks affect the propagation of the crack.
- It is necessary to accumulate the experimental data in order to evaluate these phenomena.

Summary

- Many innovative engineering studies are necessary to utilize nuclear fusion energy. One of the most important engineering studies is to develop the first wall facing to extremely hot plasma.
- If an edge part of the first wall is restrained, central displacement is 7.3 mm by the thermal expansion, and bending stress of the first wall exceeds the elastic limit. It is necessary to find a new device for releasing thermal expansion in the design of the first wall.
- A crack of 1.0 mm depth was assumed at the first wall of 4 mm thickness. Crack might propagate if the J-integral value exceeds fracture toughness value of SiC/SiC material. It is a future subject to study the effect of stress relaxation around the crack tip by creep in order to evaluate the J-integral value accurately.
- Present SiC/SiC composite material could not avoid the generation of micro cracks in it. Research and development of the material are necessary from the viewpoints of not only the integrity but also the leak tightness of the first wall.